Industrial Combustion Vision

A Vision by and for the Industrial Combustion Community

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Executive Summary

Combustion has been the mainstay of worldwide industrial development for the past 200 years. Combustion systems are used to generate steam and heat for use in vital manufacturing processes, to heat processing materials as diverse as metals and chemical feedstocks, and to change the mechanical and chemical properties of materials and products. These functions are critical to the production of basic manufactured goods used in all segments of the U.S. economy.

Since the turn of the century, great strides have been made in the fundamental science of combustion, yielding significant benefits to industry. However, the face that industry puts upon combustion has changed in recent years. Environmental issues such as ozone transport and global climate change are emerging as defining factors in the design and operation of combustion equipment.

Manufacturers throughout industry increasingly consider process heat and steam as commodities, viewing the equipment that supplies them as "black boxes." The restructuring of the electric utility industry has opened up new possibilities for industrial facilities to generate and sell power. Competitive forces have created new challenges but also tremendous opportunities for companies that can anticipate technological needs and emerging market trends.

For many, the development and application of new technology hold the key to transforming market demand into future profits. Unfortunately, few companies can accept the cost and risk of undertaking cutting-edge technological development to respond to rapidly evolving market needs. The complexity of new products and the intensity of global competition require that companies adopt new approaches, such as partnerships with customers and combustion researchers, for developing and applying advanced technologies.

This "vision" document represents the first step in a three-step approach adopted by the industrial combustion community to devise and implement a comprehensive technology development plan. In developing this vision, manufacturers and users of burners, boilers, furnaces, and other process heating equipment -- the combustion "industry" -- came together to acknowledge the challenges facing their industry and to determine where they want to be in twenty years. By setting strategic targets for the development and use of advanced technologies, they expect to enhance combustion's position as the preferred source of process energy through the next two decades.

The next step is the collaboration of the entire industrial combustion community (the industry plus academia and other research organizations) in developing a detailed research agenda known as a "technology roadmap," which will specify the research steps necessary for achieving the goals identified in this vision. The third and final step will be to conduct the research laid out in the roadmap to develop the new technologies that will ensure the future prosperity of the combustion industry.

What are the more specific aspects of this vision? In the year 2020, boilers will be energy-efficient, low-emission steam generators that are fuel-flexible, cost-effective, reliable, and safe. These boilers will incorporate improved materials and smart technology, including state-of-the-art automated controls, allowing their total integration into process and energy systems with minimal operator involvement.

The furnace and process heating system of the future will produce uniform, high-quality end products at high production rates with low specific fuel consumption and minimal environmental impact. This cost-effective system will be fully automated and adaptable to changing process needs and fuel availability. It will be safe, reliable, and easy to install, maintain, and operate.

Boilers, furnaces, and other process heating equipment will use burners that are robust, energy-efficient, compliant with emissions regulations, and process-friendly. The burner of the future will use advanced flame management control features, making it user-friendly, highly reliable, and very safe.

Although the goals of this vision are ambitious, expectations are that they will be fully met in the coming years through the three-step process just described. As a result, the availability of cost-effective, reliable, efficient, and low-emission combustion equipment will help U.S. manufacturers maintain their competitive global position into the next century. This vision document sets the process to achieve that future state in motion.

Industrial Combustion

Background

Combustion is the rapid chemical combination of oxygen with the combustible elements of a fuel. The common fuels — coal, oil, gas, wood, and their derivatives — have three elemental constituents (carbon, hydrogen, and sometimes sulfur) that unite with oxygen in the combustion air to produce heat. Combustion is used throughout industry to meet process steam and heat requirements and to promote changes in the form or composition of a feedstock, or of a semi-fabricated or fabricated product.

U.S. industry relies heavily on the combustion process (Exhibit 1). For example, boilers, furnaces, and other process heaters together use approximately two-thirds of the total energy used by the manufacturing industries. When cogeneration systems (typically boiler/steam turbine combinations) are included, the total contribution is even higher.

Exhibit 1. The Importance of Combustion to Industry

	% Total Energy from†		
Industry	**Steam**	**Heat**	**Combustion**
Petroleum Refining	29.6	62.6	92.2
Forest Products	84.4	6.0	90.4
Steel	22.6	67.0	89.6
Chemicals	49.9	32.7	82.6
Glass	4.8	75.2	80.0
Metal Casting	2.4	67.2	69.6
Aluminum	1.3	17.6	18.9

† At the point of use
Source: Energy Information Administration

Combustion devices are used pervasively for energy generation and waste disposal in a wide variety of industries. They combust fuels such as natural gas, oil, coal, wood, and a variety of wastes.

Over 60 percent of the fuels burned by industry are gaseous, with natural gas and refinery gas accounting for the largest portion. About one-quarter of the fuels burned are solids; the remaining 10 to 15 percent are liquid fuels. Boilers are used to generate process steam. As shown in Exhibit 2, furnaces and other process heating equipment produce direct sources of heat and are used for melting, heating, and heat treating metal; curing and forming; heating fluid; bonding; drying; calcining; clay firing; agglomeration; smelting; melting non-metallic materials; and other heating applications, particularly in the food processing and textiles industries.

This vision includes boilers, furnaces and other process heating equipment (including ovens and kilns). Other industrial heating systems not covered in the vision include waste incinerators, stationary combustion turbines, and stationary internal combustion engines.

The Industry Today

Key topics in the description of today's industrial combustion industry include the market for installed equipment, concerns of end users, and plans for future technologies.

The Combustion Market

The industrial boiler market in the United States exceeds 50,000 installed units. Industrial boilers are typically an order of magnitude smaller than power-plant boilers, with capacities of less than 250 MMBtu/hour. In fact, the majority of boilers in U.S. industry actually have capacities of less than 25 MMBtu/hour. However, the largest amount of industrial boiler *capacity* in the United States is found in the 100 to 250 MMBtu/hour size range, and a few industrial applications have approached utility scale.

Boilers are used in virtually every major industry. In terms of installed units, the food, paper, chemicals, petroleum, and primary metals industries account for about two-thirds of the total market and an even higher percentage of the installed capacity.

The industrial boiler market is dominated by systems that use purchased fossil fuels as their primary energy input. Natural gas is the most commonly used boiler fuel in industrial applications. The primary exceptions are paper and certain petroleum and metals operations, where waste

Exhibit 2. Major Process Heating Operations

Metal Melting • Steel making • Iron and steel melting • Non-ferrous melting Metal Heating • Steel soaking, reheat, ladle preheating • Forging • Non-ferrous heating Metal Heat Treating • Annealing • Stress relief • Tempering • Solution heat treating • Aging • Precipitation hardening Curing and Forming • Glass annealing, tempering, forming • Plastics fabrication • Gypsum production Fluid Heating • Oil and natural gas production • Chemical/petroleum feedstock preheating • Distillation, visbreaking, hydrotreating, hydrocracking, delayed coking Bonding • Sintering, brazing	Drying • Surface film drying • Rubber, plastic, wood, glass products drying • Coal drying • Food processing • Animal food processing Calcining • Cement, lime, soda ash • Alumina, gypsum Clay Firing • Structural products • Refractories Agglomeration • Iron, lead, zinc Smelting • Iron, copper, lead Non-Metallic Materials Melting • Glass Other Heating • Ore roasting • Textile manufacturing • Food production • Aluminum anode baking

fuels such as wood, pulping liquor, and refinery gases are readily available.

Two types of fuel-fired boilers are used by industry—watertube and firetube. In watertube boilers, tube-wall membranes carrying water and steam are exposed to the products of combustion. In firetube boilers, the products of combustion are carried in the tubes, heating the water and steam passing over them within the boiler vessel. Firetube boilers are typically used for steam production rates of less than 25 MMBtu/hour.

Boiler-related equipment includes economizers, superheaters, and air heaters, which are heat recovery devices designed to transfer heat from the products of combustion to another stream within the boiler system. Another steam-generating technology is the fluidized-bed combustor, in which fuel is burned in a bed of granulated particles that are maintained in a mobile suspension by the upward flow of air and combustion products. Tubes carrying the water to be heated are located in the bed and furnace walls.

Process heating equipment includes furnaces, ovens, heaters, reactors, kilns, incinerators, and dryers. Process heaters operate in low- to medium-temperature operating ranges, while furnaces, incinerators, and reactors cover the higher temperature ranges. The installed market for process heating equipment is on the order of 25,000 units, typically ranging in size from 1 to 400 MMBtu/hour. The largest numbers of furnaces are found in the metals, metal fabricating, and heat treating industries, followed by the glass and cement industries. Other process heating equipment such as reactors are used throughout the chemicals and petroleum refining industries.

A wide variety of process heating functions are found throughout the manufacturing sector. Furnaces are used to effect changes in the charge material, including oxidation, reduction, melting, heat treating, curing, baking, and drying. The nature of the material and the desired change dictate the process temperature. The composition of the atmosphere in the furnace can be controlled to further direct the changes in the material being processed.

Furnaces can be directly or indirectly fired. In directly fired furnaces, the flame and/or combustion products have direct contact with the charge. In indirectly fired furnaces, any contact between the flame and combustion products and the charge is deliberately avoided to prevent undesirable changes in the charge caused by such contact. Continuous and intermittent (batch) versions of both directly and indirectly fired furnaces are used in actual industrial operations.

Burners, which are used in both boilers and process heating equipment, are devices for introducing fuel and air at the desired velocities, turbulence, and concentration to establish and maintain proper ignition and combustion of the fuel. Some burners include part of the fuel preparation system in their construction.

Fewer than twenty companies in the United States manufacture boilers. A handful of large companies and numerous smaller firms manufacture furnaces and other process heating equipment, systems that are much more diverse than boilers because of their wider range of applications.

Issues for End Users

Issues of concern to today's manufacturers generally relate to environmental regulations, costs, productivity, and product quality. Decision makers in industry believe that the energy crisis has passed, and energy is no longer a major concern because of its abundance and relatively low cost. This thinking has caused some manufacturers to reduce the number of staff members with expertise in combustion systems.

Industrial decision makers sometimes view process heating systems as vendor-supplied "black boxes" that must provide the required process heat upon demand. Turnkey performance is demanded and guaranteed; little attention is given to the use of in-house talents to improve system performance.

European and Japanese companies have significantly increased their market share of the combustion equipment supply business over the past several decades. The Europeans have also aggressively pursued the expanding Third World market for combustion equipment. This intense competition has limited the penetration of U.S.-manufactured combustion equipment in these markets and has led some U.S. companies to reduce or eliminate budgets for research and development. Some equipment manufacturers now lack the technical and financial resources to develop new technologies and systems.

Future Combustion Systems

Although many energy-intensive industries are highly dependent on combustion, improvements to combustion processes are often considered outside their realm of concern. This places the burden of ensuring the continued advancement of combustion technology on the combustion community itself. It is sometimes difficult for a single company to develop a complex combustion system that meets the needs of equipment users. However, combustion equipment manufacturers and users agree that advances are needed for U.S. industry to remain competitive in the world market.

This vision of industrial combustion represents an important first step in securing that technical dominance. The next step is to develop a technology roadmap that will provide a comprehensive outline for achieving the technological goals the industry has set for itself in its vision. Preparing the roadmap will be the follow-on activity to this present document.

Key Drivers Shaping the Future of Industrial Combustion

The combustion community has identified the driving forces and issues that it believes will shape industrial combustion over the next twenty years. These drivers fall into the following categories:

- Markets and Economics
- Environmental Quality and Greenhouse Gases
- Process Improvement
- Policy and Politics
- Fuel/Oxidant Choices
- Energy Efficiency
- Enabling Technologies
- Health, Safety, and Reliability
- Research and Education

The first four categories are listed in the order of their importance to the industry. The complete list of the key drivers that have been identified by industry is quite comprehensive and is provided in Appendix B. The *individual drivers* that were given highest priority by industry are discussed by category in more detail below.

Markets and Economics

In the category Markets and Economics, industry considers the deregulation of the electric utility industry as the most significant issue relative to its own operations.

Electric Utility Industry Restructuring. The restructuring of the electric utility industry could substantially change the typical industrial combustion facility. Aside from environmental issues, it will likely be the most significant driver shaping the future of industrial combustion. New players will emerge in the generation and sale of power. Rates may go up or down depending on the power source. Some technologies that use electricity may become competitive with fossil-fuel-fired technologies, thereby reducing the demand for combustion systems.

Industries have traditionally separated electricity supply from steam or heat supply. In the restructured electricity market, there will be many more opportunities to combine the two, leading to higher system efficiencies. Industries owning powerhouses will have incentives for on-site generation of electricity. Industries may manage these facilities themselves or may sell or lease them to outside energy service providers. New cogeneration plants that can be sited, built, and installed relatively quickly will come on line as older, dirtier power plants are shut down.

It seems likely that a trade-off will occur between loss of market share to increasingly competitive electric-based technologies and increased markets for combustion in joint electricity/process heat applications. The net effect cannot be accurately forecasted; however, history has shown that deregulation of an industry has almost always increased demand for its products and services.

Environmental Quality and Greenhouse Gases

In the category of Environmental Quality and Greenhouse Gases, the industry has given highest priority to reducing air emissions to meet governmental regulations.

Emissions Reductions and Future Ambient Air Quality Standards. Industry anticipates the passage of new and more complex regulations for air emissions, and today's level of allowable emissions will be tightened as ambient air quality standards become stricter. Ozone and nitrogen oxides (NOx) have the greatest potential for impact on industry in the near term. While standards for some criteria pollutants are fairly well established, uncertainty and controversy surround emissions of other species, particularly air toxics and greenhouse gases.

Greenhouse gases are expected to be a major driver for the future of combustion because of strong international pressure to reduce emissions of these gases, specifically carbon dioxide (CO_2). Trace emissions of other greenhouse gases are also of concern when their "carbon equivalent" effects are calculated.

If needed, methods to control CO_2 from combustion will likely fall into one of three broad categories:

- increased system efficiency
- revolutionary new combustion processes
- sequestration

Greenhouse gases and their control will ultimately impact the efficiency, fuel type, plant siting, and production costs associated with the combustion process. The control of CO_2 may completely change the way industry thinks about combustion, possibly leading to revolutionary processes (for example, processes that facilitate the use of carbon sequestration). Currently, increasing overall system efficiency represents the simplest, most direct method of reducing greenhouse gas emissions from combustion.

Process Improvement

In the category Process Improvement, industry has identified the development and use of advanced controls and sensors and of systems integration and analysis techniques as crucial to increasing process efficiency and product yield.

Controls and Sensors/Systems Integration and Analysis. Improved controls and sensors and systems integration and analysis represent solutions to some of the problems associated with environmental quality, energy efficiency, and health/safety/reliability. These technologies and techniques can reduce emissions and energy use by optimizing system operation, and increase system safety and reliability by reducing unforced outages. Their benefits extend into product quality, staffing requirements, and other areas that affect overall plant economics. In some applications, present-day controls and sensors are not keeping pace with advances in burners and other combustion equipment, preventing this equipment from achieving its full potential in reducing emissions.

Controls and sensors may also influence regulations for combustion. As long as technology exists for measuring a particular emission, even at ultra-low concentrations, industry may be required to control that emission. If sensors are not advanced enough to allow this measurement in real time, however, control is very difficult.

Systems integration and analysis will be key components in the design and operation of future combustion systems. Electric utility restructuring and industry's trend toward optimizing overall process and energy needs within a plant will encourage broad systems analysis to accurately define needs and evaluate performance.

Fuel/Oxidant Choices

In the category Fuel/Oxidant Choices, industry recognizes that fuel costs and fuel availability are crucial to its choices of future technologies. The potential for a hydrogen-based economy is also a future consideration.

Cost and Availability of Fuels. The cost and availability of fuels drive the design and selection of equipment, the type of heat service provided, the amount of emissions generated, and other key factors. Over the life of an industrial heating system, expenditures for fuel are far greater than the first cost of the equipment itself. Fuel availability helps establish the level of risk involved with a particular process; if the long-term security of the fuel is uncertain, it may prevent a technically promising project from getting off the ground.

The oil crises of the 1970s created a strong incentive for the development of clean-coal technologies and other technologies using alternative fuels. When the crises disappeared, however, so did the interest in these technologies. Natural gas is the most commonly used fuel today because it is readily available and relatively cheap. If the price of natural gas were to go up, there would likely be a shift towards other fuels, necessitating process and equipment changes.

The quality of fuels is expected to decrease over the coming decades. When gradations exist, clean fuels are burned first, shortly after they are found, and will become increasingly scarce in the future. Technology to burn dirty fuel cleanly (including technology to convert dirty fuel to clean fuel) will continue to be needed by the year 2020.

Hydrogen Economy. Some industry experts consider hydrogen the "fuel of the future." This view is controversial because of hydrogen's explosive nature and its high production cost. However, hydrogen does represent a clean, potentially abundant fuel source that, with the necessary development of advanced technology, could aid in lowering carbon emissions from combustion should this become an important consideration in the future.

Energy Efficiency

Although industry does not consider energy efficiency a top driver, energy costs are always a competitive issue.

Competitive Pressures for Efficiency. System energy efficiency itself is not considered by the industry to be a major driving force because energy is and has been relatively cheap for a prolonged time, and can often be overshadowed by process or operating changes. As an economic driver, however, energy cost (as a component of levelized cost) has a much greater potential impact.

Most industries view themselves relative to their competitors, and strive to be the low-cost producer in order to remain viable in the long term. A company that can reduce its overall energy costs by reducing its specific energy usage may gain a competitive advantage, especially in the high-temperature industries where energy costs represent a large portion of overall production costs.

A future driving force for improved industrial heating system efficiency will likely be government regulations on greenhouse gas emissions rather than efficiency itself, primarily because of the current low cost of energy in the United States. However, when examining total energy expenditures across all U.S. industries, a 1 percent improvement in energy efficiency would save billions of dollars. Therefore, on an absolute basis, energy efficiency represents a very significant opportunity for economic savings.

Policy and Politics

Because governmental policy can be unpredictable, industry has identified it as a driver to which it may have to react on an urgent basis.

Government Policy. Government policy tends to add a layer of uncertainty over the fairly predictable environment in which different industries operate. Responding to societal pressures, the government regulates environmental quality and other factors that shape how industry can and does operate. The unpredictability of government policy may force industry to make sudden changes in the way it conducts business.

The Vision of Industrial Combustion

Manufacturers and users of combustion equipment have defined their vision of burners, boilers, and furnaces and other process heating equipment in the year 2020.

Burners

The burner of the future will be robust, energy-efficient, compliant with emissions regulations, and process-friendly. It will have multi-fuel capability and will use advanced flame management control features, making it user-friendly, highly reliable, and very safe.

Tomorrow's burners will produce very low emissions of NOx, CO, and unburned hydrocarbons while achieving high thermal efficiency. They will meet all applicable emissions regulations without the need for post-combustion controls. Advances in materials and technology will enable them to operate at higher process temperatures.

Reliable advanced flame management controls will improve burner safety, combustion efficiency, and system reliability. The burners of the future will be easy to integrate and have wider applicability in combustion systems. It is possible that a single burner could be capable of burning different types of fuels, including modified solid fuels and byproducts such as refuse-derived fuels.

Boilers

The boiler of the future will be an energy-efficient, low-emission steam generator that is fuel-flexible, cost-effective, reliable, and safe. It will incorporate improved materials and smart technology, including modern automated controls, allowing total integration into process and energy systems with minimal operator involvement.

The boiler of the future will be a key component of integrated process and energy systems designed to meet industrial steam, heat, and power needs efficiently and productively. Its advanced structural materials will allow it to meet demanding performance requirements while operating in harsh environments at significantly higher pressures and temperatures than today's systems. System efficiency will be enhanced through the economic recovery and reuse of residual heat in the exhaust gas, minimizing heat loss through the stack.

A key characteristic of the boiler will be fuel flexibility, including the ability to burn two or more fuels simultaneously and to switch from one fuel to another at any given time without compromising system performance. Coal will remain a viable option; processes will be developed and refined for modifying coal and other solid fuels to expand their use in boiler applications. In addition to conventional fuels, industrial boilers will be able to burn a wide variety of combustible byproducts and waste fuels.

Future boiler systems will use advanced burners that eliminate or greatly reduce emissions of criteria pollutants, carbon dioxide, and hazardous air pollutants. Solid waste generation will be reduced, and any wastes and byproducts generated by the system will be reused beneficially. The industry will approach zero discharge of effluents and will conserve and reuse water, which will be important in those areas of the country where water is scarce. Any water leaving the plant will be clean enough to drink.

Tomorrow's boilers will cost less to purchase and install and have lower life-cycle costs. Their safety and reliability will be enhanced through the use of advanced control systems and other smart technology, and improved materials. These features will allow smooth operation of future integrated process and energy systems, no matter how complex.

Furnaces and Other Process Heating Equipment

The furnace of the future will process uniform, high-quality end products at high rates of production with low specific fuel consumption and minimal environmental impact. This cost-effective furnace will be fully *automated and adaptable to changing process needs and fuel availability. It will be safe, reliable, and easy to install, maintain, and operate.*

The furnace (and process heating equipment) of the future will remain sufficiently cost-effective in manufacturing applications to maintain its status as the preferred choice of energy services in U.S. industry. Advanced combustion technology will help to maintain the country's position as the world leader in manufacturing that requires process heat.

Industry will respond to international efforts to reduce carbon dioxide and other greenhouse gas emissions by developing advanced, environmentally friendly process heating and burner technology and alternative system fuel capabilities, and adopting other techniques to reduce greenhouse gases. Emissions of criteria pollutants and air toxics will be minimized.

Tomorrow's process heating equipment will be able to adapt to virtually any fuel situation by burning multiple fuels efficiently, including waste and renewable fuels, and burning dirtier fuels more cleanly than ever before. Advanced design and technology will allow on-line fuel switching to accommodate fluctuating fuel availability and cost.

The fully automated furnace of the future will maintain the highest standards of safety, virtually eliminating accidents. Reliability will be optimized for a range of operating conditions to minimize downtime and maximize productivity.

Future process heating equipment will be extremely flexible. Industry will become adept at using advanced modeling techniques that allow quick response to changing operating requirements and product specifications, reducing product lead times and optimizing efficiency and product quality. Advances in enabling technologies, including robust sensors and active-control feedback systems, will improve the performance of process heating equipment industry-wide without compromising reliability.

Strategic Targets

The industry has established a number of strategic targets for boilers, furnaces, and other process heating equipment that it would like to achieve by the year 2020. These targets are directed toward the key drivers the industry has identified (i.e., environmental quality, fuel flexibility). Many of these targets also relate to concepts from the vision statements, while others represent goals in supporting areas. Strategic targets for burners are incorporated into the boiler and furnace targets, particularly in the category of environmental quality.

Boilers

Users and manufacturers of boiler systems have jointly agreed on the need to improve the equipment's performance, flexibility, and cost-effectiveness. To this end, they have identified a number of strategic (performance) targets for boiler systems and related equipment in the areas of environmental quality, fuel flexibility, energy efficiency, materials performance, safety and reliability, and cost-effectiveness (summarized in Exhibit 3). They have also articulated the need for integrating boilers into process and energy systems to address plant-wide demands for steam, heat, and power.

Environmental Quality. Air emissions, particularly when burning solid and liquid fuels, are the most critical environmental concern associated with boiler operation. By 2020, those emissions that cannot be eliminated will be reduced to the lowest level possible. For gaseous fuels, the industry has targeted reducing

- NOx to less than 2 ppm,
- CO to less than 5 ppm,
- Volatile organic compounds and unburned hydrocarbons to less than 1 ppm, and
- Particulate matter to less than 0.003 pounds per million Btus of fuel burned.

The industry will approach these targets as closely as possible for liquid and solid fuels, but will make allowances for differences in fuel types. Coal is the primary solid fuel used today and will likely remain so in the future. The use of alternative solid fuels, including hard-to-burn fuels (waste tires, for example) will increase throughout industry. The target is removal of more than 98 percent of the sulfur dioxide (SO_2) emitted during combustion of both liquid and solid fuels in boilers.

Water use and solid waste generation and utilization are also of concern to the industry. Water reuse will be maximized, with boiler facilities approaching zero discharge. All environmental regulations on water cleanliness will be met; optimally, water leaving the plant will be drinkable.

Exhibit 3. Performance Targets for Boilers

Environmental Quality

1. Reduce criteria pollutants for gaseous fuels
   - Reduce NOx emissions to <2 ppm
   - Reduce CO emissions to <5 ppm
   - Reduce particulate matter emissions to <0.003 lbs/10^6 Btu
   - Reduce volatile organic compounds and hydrocarbons emissions to <1 ppm

2. Approach gaseous fuel targets as closely as possible for solids and liquids
   - Achieve >98 percent SO_2 removal

3. Shift toward fuel-neutral, output-based standards

4. Reduce CO_2 emissions
   - Respond to worldwide CO_2 reduction pressures by maximizing system efficiency

5. Reduce hazardous air pollutants
   - Meet or exceed requirements

6. Reduce solid waste
   - Maximize by-product utilization

7. Reduce wastewater
   - Maximize water reuse (zero discharge)
   - Meet all environmental regulations

Fuel Flexibility

8. Consider all combustible byproducts as potential fuels

9. Develop the ability to burn different fuels simultaneously

10. Develop on-line fuel switching capability

11. Promote use of renewable and waste fuels in the United States

Energy Efficiency

12. Maximize system efficiency

13. Minimize stack temperatures via residual heat recovery
    - Achieve 150°F stack temperature

14. Integrate boilers with more advanced thermodynamic cycles (including alternative working fluids)

Process/Energy Compatibility

15. Integrate steam and power requirements with process plants

16. Install cogeneration systems as the rule rather than the exception

Safety/Reliability/Maintainability

17. At minimum, maintain current levels of safety

18. Improve system reliability by 50 percent

19. Increase time between scheduled outages by 100 percent

20. Eliminate trips due to control malfunction

Materials

21. Develop reduced-cost materials able to exceed 1,050°F in superheater and higher operating pressure

22. Develop inexpensive, corrosion-resistant materials that are able to function below 140°F

23. Improve the heat transfer coefficient

24. Improve performance (erosion and corrosion) at higher temperatures and pressures

25. Improve material welding/joining

26. Enhance refractory performance

27. Integrate catalysts within the boiler itself

Cost Effectiveness

28. Lower first cost of equipment

29. Lower life-cycle costs

30. Promote government regulations that encourage adoption of new technologies

31. Promote government incentives for investment in efficient technologies

Policy

32. Promote importance of boilers to U.S. economy

Minimizing wastes will become increasingly important in the future. Waste minimization will be achieved through efficiency improvements but also through a variety of alternatives. Companies will maximize the utilization of boiler system byproducts by reusing them within the plant or finding beneficial uses outside the plant. With a fuel-flexible system, many process wastes can be used as fuel if they have adequate heating value.

Fuel Flexibility. Waste fuels, biomass, and other renewable fuels represent important sources of energy that will be tapped by industry in the future. Up-front processes may be used to convert these fuels into a form that is more compatible with today's combustion equipment. Ensuring the capability of using both home-grown fuels and waste fuels is critical to national security. Additionally, all combustible byproducts will be considered as potential boiler fuels.

The boilers of the future will be able to burn different types of fuels simultaneously and switch fuels on-line without having to shut down. Caution must be exercised in this regard, however, so that boiler performance is not excessively compromised. The use of smarter systems incorporating such features as neural networks and feedback controls should facilitate the design and use of multi-fuel systems.

Energy Efficiency. Three factors play a role in determining the efficiency of a boiler system:

- Fuel characteristics (e.g., moisture)
- Design considerations (e.g., operating temperatures)
- Controllable operating variables (e.g., excess air)

Industry gives priority to overall *system* efficiency (rather than combustion efficiency) as the standard industry measurement of the future. Currently, those factors over which the operator has the least control are typically the factors that have the most influence on system efficiency. If boilers are to play a large role in meeting future steam generating and energy requirements, they must be integrated into highly efficient systems. While there are limitations on the efficiency gains that can be achieved within the boiler itself, the operation of the system as a whole presents significant opportunity for improvement. The boilers of the future must be adaptable to potentially complex process systems.

With these requirements in mind, industry will seek to maximize system efficiency while striving for total system adaptability. Heat losses from the stack will be minimized, in large part through the recovery of residual heat that will be used within the boiler house or elsewhere within the plant. A high priority for the industry is to reduce the temperature of the gas leaving the stack to approximately 150ºF, representing a gain of nearly 5 percentage points in system efficiency. Efficiency gains may also be realized through the integration of the boiler with more advanced thermodynamic cycles, including those using alternative working fluids.

Process/Energy Compatibility. Industry will become increasingly sophisticated about evaluating its process and energy needs, both current and potential, and designing solutions that optimize system efficiency, productivity, and environmental performance. The integration of steam and power requirements with process plants will be key; cogeneration will be the rule rather than the exception. Any manufacturer who installs a boiler should anticipate that there may be an opportunity to generate electricity in the future. Manufacturers will accommodate process conditions and try to balance the electric and steam production to the most efficient cycle.

Safety/Reliability/Maintainability. Boiler operations will continue to be at least as safe as they are today, with safety levels likely to rise as a result of advances in robust control system technology. Advanced combustion systems are complex, incorporating numerous controls and sensors. Currently, the majority of reliability problems related to boilers are associated with controls and auxiliary equipment rather than the boiler itself. "Nuisance" trips due to control malfunction present an unwanted burden and will be eliminated. Overall system reliability in 2020 will be 50 percent higher than current levels.

Maintainability is directly related to reliability; a boiler system that is well-maintained is more reliable. The average time between scheduled outages for boiler systems will be increased by 100 percent, so that a system on a one-year scheduled-maintenance cycle today will be on a two-year cycle in 2020.

Materials. Advances in materials technology will help industry achieve some of its goals in the areas of efficiency, fuel flexibility, and cost-effectiveness. Boiler systems will be capable of operating in an acid-gas environment at higher pressures and temperatures (exceeding 1,050ºF in the superheater) using economical advanced materials that resist corrosion, erosion, and degradation of material properties. On the condensing side, new materials will enable systems to operate below

140ºF without acid-gas corrosion. Improved refractories and insulation materials, improved welding and joining technologies, and novel catalyst systems will also enhance boiler performance.

Cost Effectiveness. Boiler systems in the year 2020 will have lower capital and life-cycle costs in response to competitive international market pressures. Future boilers are more likely to be modular in nature, and the strong trend toward the use of standardized system packages will continue.

The industry sees the need for a strong government role in promoting the adoption of new energy-efficient, environmentally sound technologies. Without a clear incentive, a company will typically invest available capital in improving its manufacturing processes rather than upgrading its boiler system. Government incentives — both financial and regulatory — could encourage industry to shift from older, inefficient equipment to newer technologies, benefitting industry and the nation as a whole.

Furnaces and Other Process Heating Equipment

Analyzing the key drivers that are expected to shape combustion needs in the next twenty years, the furnace and process heating equipment community has also defined strategic (performance) targets that reflect its vision for 2020 (Exhibit 4). Many of the targeted areas—environmental quality, energy efficiency, fuels, safety and reliability—are identical to those identified by the boiler community.

Environmental Quality. The industry perceives its most critical target for 2020 to be a 90 percent reduction in all air emissions from furnaces and other process heating equipment (including toxics but excluding CO_2) relative to uncontrolled 1990 levels. This is particularly challenging because the emissions reduction target is on an absolute basis and does not make any allowances for market growth. Carbon dioxide emissions should be reduced to levels consistent with future targets of international agreements.

Fuels and Oxidants. Maximum fuel flexibility is critical to ensuring the efficient and economic operation of process heating systems if certain fuels become scarce or costly. Accordingly, the process heater of the future must

Exhibit 4. Performance Targets for Furnaces and Other Process Heating Equipment

Environmental Quality

1. Reduce all air emissions by 90 percent by 2020
2. Reduce CO_2 emissions to levels agreed upon by the international community
   – Increase efficiency
   – Achieve higher hydrogen-to-carbon ratio
   – Practice carbon sequestration
   – Increase use of biomass

Fuels and Oxidants

3. Maximize the ability to use multiple fuels, including waste and renewable fuels
   – Increase adaptability to emerging technologies

Energy Efficiency

4. Reduce specific fuel consumption (Btu/constant dollar of product) by 20 to 50 percent by 2020

Process Improvements

5. Reduce product loss rate by 50 percent
6. Enhance system integration and analysis
7. Increase response rate/reduce lead times to new technical conditions through faster modeling and application
   – Shorten lead-time from concept to saleability by 50 percent
   – Educate industry about the limitations of models

Safety/Reliability

7. Implement and achieve highest safety standards for furnaces to attain zero accidents
8. Maximize system robustness without compromising product quality and emissions
   – Increase scheduled maintenance cycle to 5 years

Research and Education

9. Strengthen link between industrial needs and academic resources

Cost

10. Reduce the total cost of combustion in manufacturing to maintain its status as the preferred choice of energy services
11. Introduce advanced combustion technology to maintain the United States as the world leader in manufacturing that requires process heat

be able to burn multiple fuels, including waste and renewable fuels, without jeopardizing efficiency or environmental performance. Additionally, process heating equipment must be adaptable to emerging technologies so that large capital expenditures will not be necessary to retrofit a furnace or other process heating system with new technology.

In light of fluctuating fuel prices, "least-cost routing" for fuels could be possible with sufficiently flexible process heating equipment. Flexibility will be accomplished with equipment that is quickly, easily, and economically adapted to different fuel types or with burners that can accommodate multiple fuel types.

Energy Efficiency. If future international targets on CO_2 emissions are to be met or even approached, the energy efficiency of furnaces and other process heating equipment will need to be improved. By 2020, users of industrial furnaces will have reduced specific fuel consumption (energy input per unit output) by 20 to 50 percent, achieving increased process energy efficiency. The amount of efficiency improvement that can be gained varies according to the industry, with a few industries falling outside of the aforementioned range. The downstream processes of energy recovery and reuse are by themselves not adequate for increasing efficiency; improvements must be made in the performance of the furnace and burner themselves.

Existing methods for increasing energy efficiency in process heating systems are not always economical and may find limited use. More efficient technologies must be made affordable to encourage their adoption by industry.

Process Improvements. Improvements in process heating (and burner) technology will allow future process heating equipment to operate more predictably and uniformly, resulting in higher product quality. The average loss rate of product in 2020 will be 50 percent lower than today. In many applications process heating equipment will be integrated into plant-wide energy systems, maximizing operating flexibility and plant efficiency. User-friendly computer models addressing key technical issues will be developed and made available on a more timely basis (with lead times half as long as current ones), yielding usable results sooner. Industry will be educated about the capabilities and limitations of these new models.

Safety/Reliability. The process heating system of the future must be adaptable to changing process needs and flexible enough to perform optimally under different operating conditions, with minimal toxicity failure modes. It will operate using the highest safety standards, and accidents will be minimized. Process heating equipment will be designed for maximum flexibility and robustness without adversely affecting product quality or environmental performance. System reliability and performance will be improved so that preventive maintenance schedules can be lengthened to an average of five years, reducing equipment downtime and the associated impacts on plant productivity.

Research and Education. Process heating equipment suppliers and users will work together to identify future process heating needs and to discuss options for cooperative research. Stronger links between the industry and appropriate research institutions will ensure that top priorities are being met.

Cost. Combustion must become a smaller share of total manufacturing costs if combustion is to remain the preferred choice of process heating services. The combustion industry must be dynamic enough to compete should an unforseen revolution occur in process heating, offering a new energy-transfer mode.

The United States will develop and market advanced combustion technology to maintain its global leadership in manufacturing that requires process heat and in combustion technology itself.

Key Competitive Challenges

As discussed in the previous section on "Strategic Targets," the combustion community has established a set of aggressive goals for the year 2020. To achieve these goals, the industry must overcome a number of key challenges in the following areas:

- Technology
- Energy and Environment
- Fuel Choices
- Markets and Economics

The industry also faces two broad, cross-cutting challenges:

- **The Unpredictability of the Future.** It is impossible to know the environmental regulations that will be enacted, how competitiveness will change in world markets, the fuels that will be available and their prices, and the impact that utility restructuring will have on the combustion community.

- **The Need to Look at Combustion Equipment as Part of an Overall System.** A multitude of sometimes unpredictable inputs (equipment, fuels, environmental regulations, and policy constraints) and their complex interrelationships must be considered in a broad systems analysis to optimize system efficiency and environmental performance.

In the future, industries using combustion will need to be flexible and adaptable in order to respond to these types of uncertainties.

The specific issues that the industry must consider to meet these key challenges have already been addressed in previous sections. However, they are discussed further under the appropriate challenges, below.

Technology

The competitive technological challenges include the following:

- **Developing advanced heating techniques that are cost-effective and non-damaging to the environment.** The industry acknowledges that major advances are needed in combustion technology, which may be incremental steps or novel, innovative changes that make significant improvements in boilers and process heating equipment.

- **Improving controls and sensors for industrial heating technology.** Robust feedback control and ultimately fully automated operation will increase system performance and therefore productivity and product quality.

- **Designing software tools for combustion.** With a more complete understanding of design parameters, and routine systems integration and analysis, industry will develop a greater range of applications for industrial heating equipment.

- **Optimizing heat-transfer practices and advanced, residual heat-recovery systems in future boilers and process heating equipment.** Greater understanding of beneficial application of advanced thermodynamic cycles (including alternative working fluids) will allow equipment to be more thermodynamically efficient than ever before. Flexible combustion equipment will be able to burn a variety of waste fuels efficiently and cost-effectively.

- **Developing improved materials in synergy with technological advancements to achieve higher efficiencies.** Materials with enhanced capabilities are needed to overcome the limitations imposed on current combustion systems by conventional materials. New corrosion-resistant materials for better heat transfer and innovative catalytic materials will broaden the range of operating conditions and design possibilities available to combustion equipment. Thinner, lighter insulation and refractory materials will reduce generation of solid wastes and allow the use of smaller systems with the same output capacity.

Energy and Environment

The competitive environmental challenges will focus on meeting government regulations and policies, particularly those related to global climate change. Advanced environmental industrial practices will include the following:

- **Lowering the levels of emissions.** While allowable emission levels of some pollutants are reasonably well settled, others are highly uncertain. For example, the degree to which CO_2 and air toxics will be regulated in the future is unknown but is expected to have a major impact on the way U.S. industry operates.

- **Addressing the role played by efficiency in determining emissions outputs.** Energy efficiency, because of its direct effect on environmental quality, is a key component of the environmental challenge to combustion. Accordingly, many technology developments in industrial heating systems over the coming years will increase energy efficiency, enabling industries to more easily control criteria pollutants and other emissions.

- **Shifting to fuel-neutral, output-based, air-quality standards.** Working with these standards will require the ability to calculate the efficiency of complex systems whose boundaries may not be clear-cut. This capability must be developed as part of the industry's increased emphasis on systems-level thinking.

Fuel Choices

The most influential factors in the selection of combustion equipment are fuel cost, availability, and security. Competitive challenges the industry must meet related to fuel choices include the following:

- **Avoiding making equipment choices on the basis of first cost.** Over the lifetime of the typical boiler or process heater, the cost of the fuel used is far greater in value than the capital cost of the equipment itself (although capital cost is obviously an important consideration).

- **Realizing that fuel security in the future is unpredictable.** Future combustion equipment must be flexible and able to operate under varying scenarios of fuel availability and cost. The ability to burn multiple fuels using the same equipment may be developed for a range of industrial burners. On-line fuel switchability would enable industrial users to optimize fuel selection and cost.

- **Developing cleaner methods of burning dirtier fuels as clean fuel sources are depleted in the next century.** The ability to burn alternative fuels, especially waste fuels, must be fully developed to ensure a secure energy source.

Markets and Economics

The upcoming twenty years will be a dynamic time for combustion markets and for the industries that operate combustion systems, and there are important competitive challenges in the market and economics arena:

- **Meeting tough competition from foreign manufacturers, particularly in Third World countries, that threatens the U.S. position.** Changing regulations, market trends, and the emergence of new players in world markets are affecting the way many industries do business. The face of the industrial combustion facility will change with the restructuring of the electric utility industry. Even the industrial mind-set is changing -- many industries are increasingly regarding heat as a commodity that they want delivered reliably, safely, and quickly.

- **Taking advantage of the opportunity and incentive presented by electric utility restructuring for industrial combustion users to expand their traditional business into cogenerating electricity.** Greater integration of process heat and steam supply and electricity supply will lead to more efficient process systems and fewer combustion emissions. Taking full advantage of this new market will require broad, comprehensive systems analysis by potential industrial players. Cheaper electricity could also challenge process heat and steam in some applications, and manufacturers of combustion equipment must take steps to ensure combustion remains competitive.

- **Becoming a low-cost producer.** Increased international competition presents another challenge to U.S. combustion markets. Market competitiveness will continue to drive costs down with the continued move to a world-sourced economy. Over the long run, cost-effectiveness, efficiency, and reliability provide incentives for early adoption of more modern systems.

- **Reducing the life-cycle and first costs of combustion systems.** The life-cycle costs and first costs (cost of installing the equipment) of combustion systems must be reduced in order to maintain combustion as the preferred method of supplying process heat to manufacturing. The development of cost-effective, efficient industrial combustion systems can also help ensure that manufacturing capacity stays in the United States, helping maintain this country's leadership position in manufacturing requiring process heat.

Next Steps

The combustion community has adopted the "Industries of the Future" approach or strategy promoted by the U.S. Department of Energy to plan for technology development. This approach provides a three-step process for devising and implementing a comprehensive technology development plan. The vision is the first step. Based on the broad goals identified in this vision, the industry will then develop a detailed research agenda, known as a technology roadmap, that specifies the research steps necessary for achieving the vision. Finally, the research will be implemented, often through collaborative research partnerships composed of private companies, suppliers, trade associations, national laboratories, academia, private research institutions, and government agencies.

The Industries of the Future strategy already has been embraced by a number of energy-intensive industries, including steel, aluminum, metal casting, glass, forest products, and chemicals. Each of these industries has developed a vision, and many of them have published technology roadmaps. A cross-cutting combustion technology roadmap will be developed that incorporates the research needs the combustion community has identified for itself. In addition, the results will be available to the Industries of the Future to help them meet their specific combustion needs. This document will help the combustion community develop a comprehensive industrial combustion research agenda that addresses both generic and industry-specific needs.

The technology roadmap will identify current technologies, barriers to achieving performance targets, and technology options for overcoming the barriers. It may also specify technical requirements where appropriate, set priorities among the suggested R&D activities, and establish research pathways. To develop this roadmap, industry will solicit the participation of representatives of the relevant stakeholder groups that will influence or be affected by advances in industrial combustion technology. A group of technologists drawn from users, manufacturers, the research community, and industry associations will develop a draft roadmap, which will be distributed for comment and input to a larger group of stakeholders.

The ultimate value of the technology roadmap is its ability to align research across industry, academia, and the federal sectors. In a recent assessment of industry's technology needs, the Council on Competitiveness determined the formation of R&D partnerships to be the single most important step toward meeting tomorrow's technology and market challenges. By articulating its own technology strategy, the U.S. combustion community hopes to motivate companies, the academic community, and the national research infrastructure to refocus their research efforts in line with industry's needs.

Appendix A: Contributors to the Vision

This vision document was prepared by Energetics, Incorporated based on input provided by the following participants in a facilitated workshop held in January, 1998.

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Appendix B: Key Drivers

Key Drivers That Will Shape Future Combustion Needs In Industry

(✪ = Top Priority Area; ● = High Priority Driver)

Markets and Economics ✪✪✪✪✪✪✪✪	Environmental Quality and Greenhouse Gases ✪✪✪✪✪✪✪	Process Improvement ✪✪✪	Policy and Politics ✪✪✪
Electric utility industry restructuring ●●● Increased reliability demands and guarantees ●● Loss of U.S. manufacturing global position ● Tougher international competition ● Industry focus on core business and outsourcing of energy ● Increased focus on Third World markets ● Third World realization that the United States is its only market Increased competition with Third World products Shift of U.S. productivity to Third World Keeping pace with ever-growing production needs and outputs Downsizing for Wall Street Value creation Lowest first cost of combustion systems Market characterization and cost tolerance for new products Faster product life cycles Growing demand for short-term profits Move towards distributed energy base Producing product at lower cost Trend away from conventional combustion - Move to fuel cells and gas turbines Availability of capital for new, improved equipment New processes requiring combustion	Emissions reductions ●●●●●●● - Environmental extremism ● - Zero emissions ● Future ambient air quality standards ●●●●●●●● Global climate control ●●●●● - Greenhouse effect (real or perceived) - CO_2 concentrations and sequestering - Critical regulations on CO_2 emissions The need to continuously monitor emissions and performance ●●● Lowest achievable emissions at reasonable cost ●● International pollution regulations ● Pollution prevention ● Sustainable development ● Emission control Trace emission regulations Life-cycle cost of environmental performance Industrial ecology Constant emissions at very high turndown ratio Tighter standards for ozone and fine particulate matter and on CO_2 emissions	Availability of improved controls and sensors ●●●●●● Increased systems integration and analysis ●●●● Active feedback control ●● The need to extend life of existing equipment while lowering emissions ●● The need to reduce heat requirements in processes ● More capacity from smaller units ● Maintenance requirements ● Increased water quality control Higher process output temperatures Matching combustion to process needs Changes in parameters in steam requirements (temperature, pressure) Yield improvements from furnaces Use of diagnostic controls Higher quality products through process design Debottlenecking Active control with on-line process simulations Low-level heat-recovery systems Need to increase capacity Technology changes that impact need for energy Fully automatic operation - No instrument maintenance Rapidly growing technology base	Government policy ●●●●● Factors outside combustion that affect fuel use ● Litigation trends Lack of government energy awareness Energy self-independence (e.g., cogeneration) Potential for Middle East energy crises Energy security (more coal) Potential for more cooperation (e.g. government/industry research) Uncertainty over future environmental issues and regulations

Key Drivers That Will Shape Future Combustion Needs In Industry (cont)

(✪ = Top Priority Area; ● = High Priority Driver)

Fuel/Oxidant Choices ✪	Energy Efficiency ✪	Enabling Technologies	Health, Safety, and Reliability	Research and Education
Cost and availability of fuels ●●●●	Competitive pressures for efficiency ●●●●●	New materials and materials science ●●	Enhanced safety reliability ●	Unified energy program between DOE and EPA ●●●
Ability to burn dirtier fuels more cleanly ●●	More effective use of low-grade heat ●	Combustion equipment to burn new waste fuels efficiently ●	Elimination of single-point failures	Loss of energy operators with knowledge ●
Availability of advanced hydrogen-generation technology ●● - Cost of hydrogen	Continuous efficiency monitoring systems	Flameless combustion ●	Reduction of failure modes with regard to emissions	Changes in engineering curriculums at universities
Move to a hydrogen economy ●	Improved efficiency of fuel utilization	Combustion design software tools ●	National desire for clean service-type jobs	
Variations in fuels available	Higher use of condensable heat exchangers	Advances in catalytic materials ●		
Use of biomass	More utilization of combustion by-products	Advanced air separations system to reduce oxygen costs		
Development of renewable fuel sources	Heat ratios (cogeneration)	Materials to get better heat transfer with less corrosion		
Oxy-fuel combustion		Compact design with better material durability		
Fuel reforming		Ways to take good ideas and make them viable for small users		
Uncertainty about fuel additives and conditioners		Higher automation for combustion		
The need to be able to burn multiple fuels in same boiler		Integration with existing and new technologies		
Uncertainty over types of fuels available in the future		Increased productivity via heat transfer optimization		
		Material costs		
		Lower volume insulation and refractory materials		
		Availability of low-cost electronics		
		"Jones" syndrome (keeping up with computer development)		
		Better combustion modeling capability		
		Wider implementation of modular design		